# Development of a Skeletal Model Arm

## 5. Development of Anatomically Analogous Forearm Joints

## 6. Development of an Anatomically Analogous Elbow Joint

## 7. Development of an Anatomically Analogous Wrist Joint and the Evaluation of the Skeletal Model Arm

**Over view**

The work presented in the following three chapters represents the second cycle in the development of the articulated model skeletal arm.

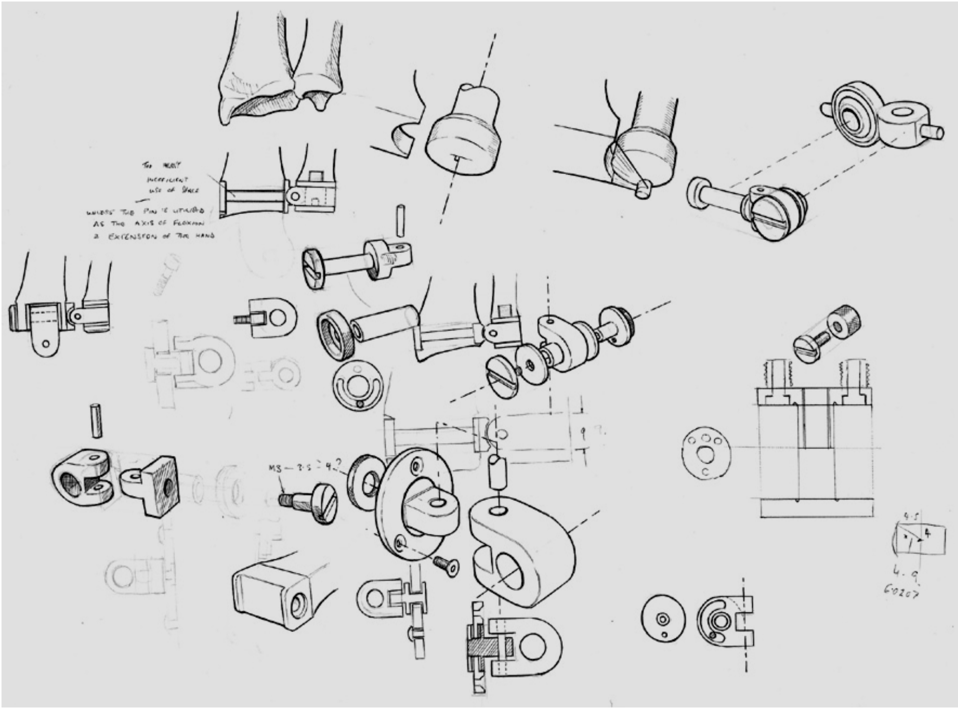
The creative reasoning process appeared successful in the development of the skeletal model hand, therefore, it is used again in this cycle of development.

From the evaluation of the model hand it was evident that the most successful analogies of the joints were those that were the most closely observed in the creative reasoning stages. Therefore the following chapters are characterised by more thorough observation and literature review.

As with the model hand, extensive qualitative evaluation has found not to be meaningful until significant sections of the articulation of the limb are complete. Therefore, the main evaluation features at the end of these chapters once the whole model limb has been assembled.

Similar to the presentation of the chapters on the model hand the following chapters use the drawing produced as part of the development work to explain the path of development of the model limb.

# 5. Development of Anatomically Analogous Forearm Joints



**A Sketch Sheet Used in the Development of Forearm Joints**

The forearm was taken as the next anatomical segment for analogy as it is the next proximal section of the upper-limb.  Additionally, the design of joints for an analogous forearm are required to complete the articulations evident at the level of the wrist.

The methods used to study the joins of the forearm were similar to those used in the chapters detailing the development of the model hand.  However, it was found that additional mathematical analysis was required in the design stages to assess potential linked joint configurations

The diagram above is an example of  one of the sketch sheets used in the development of the forearm joints.  Details from such sheets are used as figures and referenced in the text to elucidate the development of the joints

This chapter starts with a summary of the prosthetic devices that provide articulations that roughly approximate those of the forearm.  A brief description is then given of the anatomical movements of the forearm, pronation and supination.  This is followed by the detail of the creative reasoning process applied to the study of the forearm, and the development of analogous concept joints.

This chapter finishes with the movements permitted by the joints designed being quantitatively compared with an intact human arm using specially designed splints.

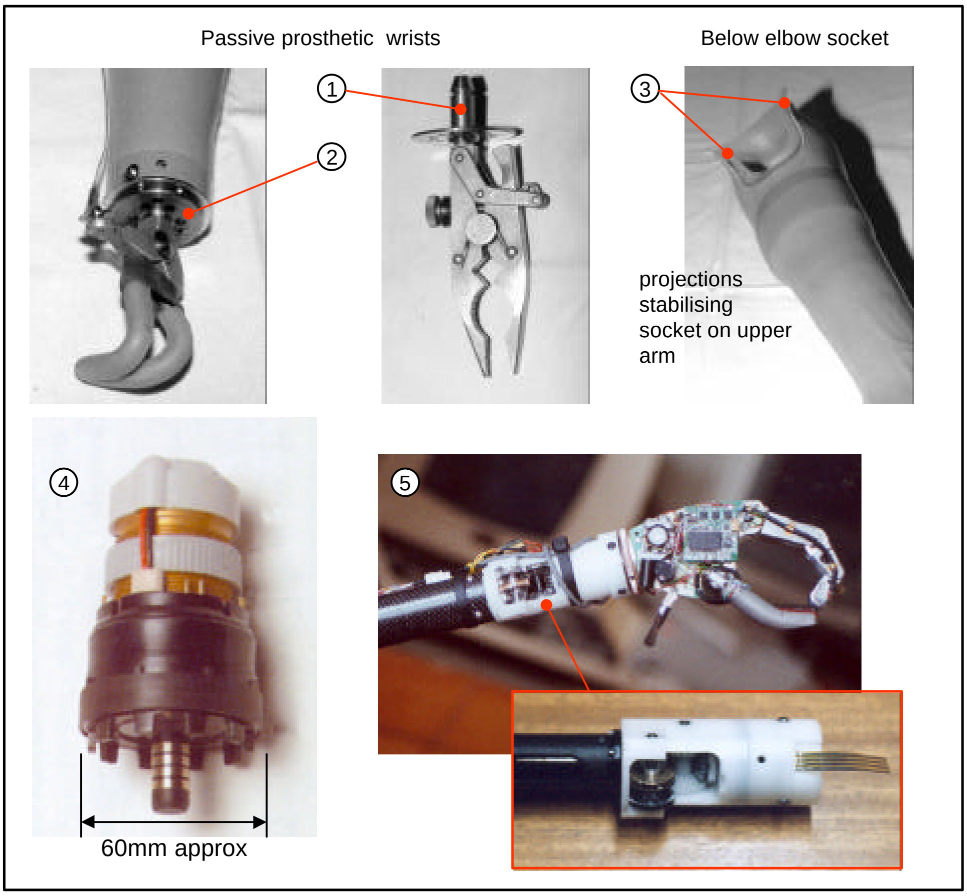



**Fig 5.1 Prosthetic Wrists offering Pronation and Supination**

Body-powered upper limb prostheses usually incorporate a passive wrist. This often consists of an axial strut (1) around which the terminal device rotates. The strut is connected to a circular steel plate with a concentric ring of holes drilled through it (2). A correctly positioned detent on the socket locks the axial angle of the terminal device by projecting though one of the holes in the ring. These devices are for use by unilateral amputees, as their action relies on the amputee orientating their prosthetic wrist with their intact hand, before attempting a task. The mechanical rotation of the wrist becomes important as it has been regularly observed that below elbow amputees showing some residual pronation and supination have prosthetic sockets stabilised on their arms in such a manner that this rotation is locked (3) (Martin 2000). The mechanical wrist arrangement permits the wrist unit to be rotated through 360 degrees much farther that the normal human range of motion in pronation and supination (Kapandji 1982).

The fitting of powered prosthetic wrists is becoming more common (Martin 2000). However, problems still remain in their control (Datta and Brain 1992) and from the increased weight and bulk to the prosthesis (Martin 2000). It can be seen from the Otto Bock powered wrist shown (4) that, like the elbow, to achieve appropriate power from a 6 volt DC electric motor requires a bulky gear mechanism. Figure 5.1 (5) shows current research into reducing the bulk of this gear mechanism by using a differential type gear arrangement. In this mechanism planetary type gears attached to the motor that drive a “worm” gear which is then connected to a crown wheel that finally drives a bevel gear connected to the terminal device.

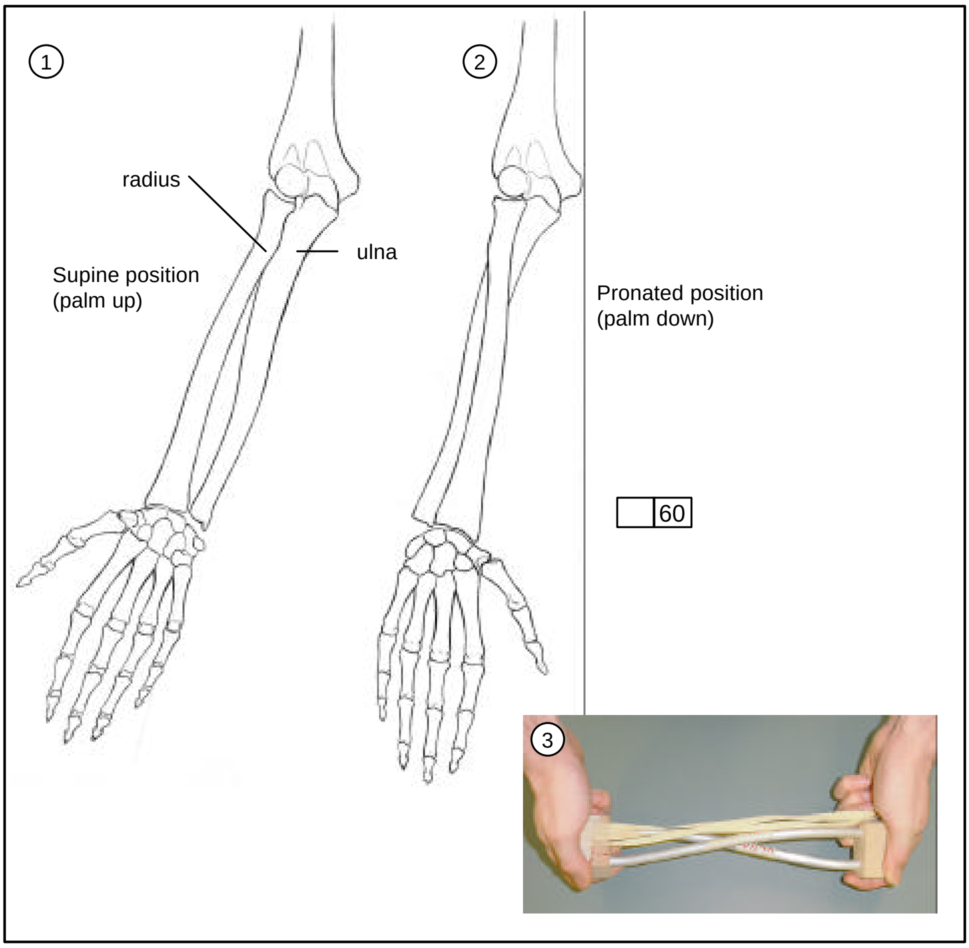



**Fig 5.2 Initial Sketch Ideas**

Rotation of the human forearm occurs by the rotation of the radius bone about the ulna (Smith et al 1996). With the arms by the sides and the palms facing forward, the forearm is said to be supinated. If the palm is then rotated medially towards the body with the palm facing backwards, then the forearm is pronated. In the supinated position (1) the radius and ulna run parallel to one another, whilst in the pronated position the radius crosses the ulna (2) (Kapandji 1982). For this to occur the bones need to be cranked along their length. To understand the cranked nature of these forms a simple model was made using two aluminium rods (3).

This mechanical arrangement appears much more complex than that of the simple axial strut necessary to achieve a axial rotation. However, the strength of the hand may be attributed to the comparatively large extrinsic muscles of the hand that are situated in the volume of the forearm (Kapit and Elson 1993, Chao et al 1989). The extrinsic finger tendons must pass through the wrist. This passage would not be possible if the wrist simply rotated on a single axial strut (Kapandji 1982). Kevlar bands were used on the simple model to examine how the extrinsic tendon action remains unimpeded by forearm rotation (3). To replicate the movement of the forearm closely for cosmetic purposes, and to allow the potential for anatomically analogous actuation the apparently more complex anatomical solution to long axis wrist movement was chosen for a basis of mechanical analogy.

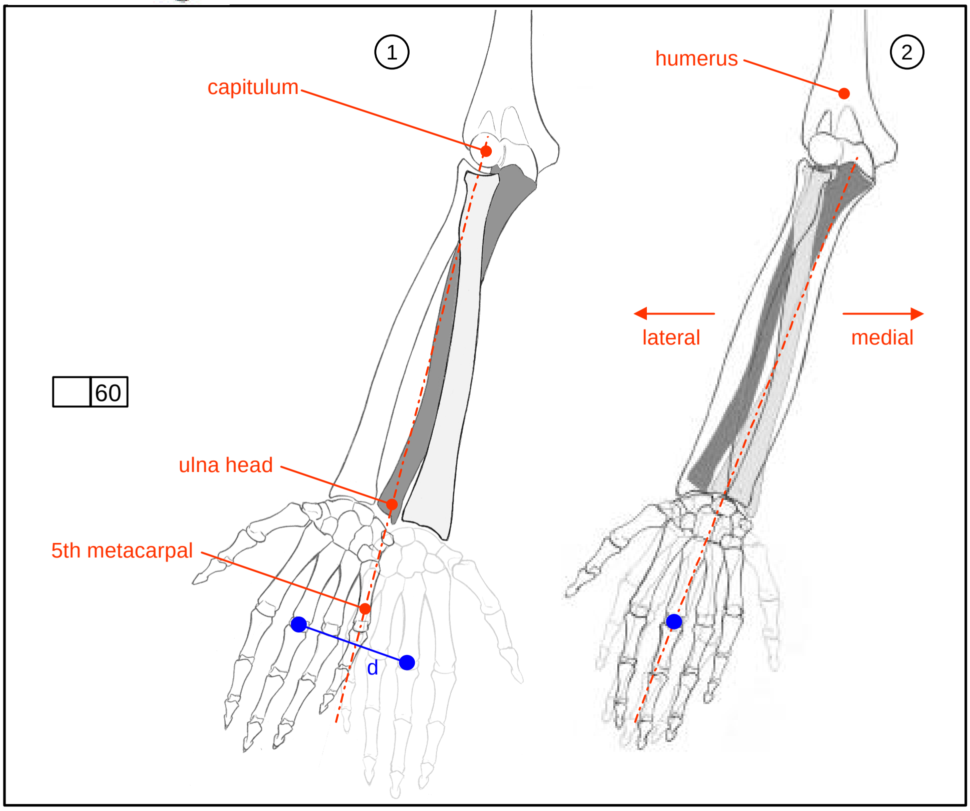
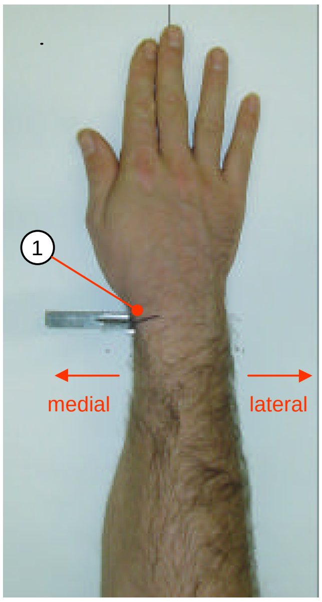



**Fig 5.3 The Axis of Forearm Rotation**

Biomechanics texts indicate that the rotation of the forearm can be considered to occur along a line extending from the centre of capitulum to the approximate centre of the head of the distal ulna (Smith et al 1996, Norkin and Levangie 1992). It can be seen from figure 5.3 (1) that if this centre line is extrapolated to the hand then it extends through the fifth metacarpal (small finger). Therefore, as the forearm is rotated, a point on the 3rd metacarpal can be seen to move a distance *d*. However, other anatomical texts additionally refer to an 'axis of pronation-supination' (Kapandji 1982). This axis extends through the centre of the third metacarpal, with the effect that the hand may be rotated without consequent translation of the third metacarpal (Amis 1990). During forearm rotation the distal ulna appears to translate medially to laterally as the arm is pronated and reverses in direction as the arm is supinated. Kapandji indicates that when the elbow is flexed at 90 degrees, apparent translation of the distal ulna head may be due to compensatory movements of humeral rotation (Kapandji 1982). In order for the distal ulna head to translate without compensatory rotation of the humerus requires either that there is a rotation between the humerus and proximal ulna (humero-ulnar joint), or that the ulna itself is deforming. There is no radiographic evidence for distortion of the form of the ulna contributing to pronation-supination movements, therefore, debate has focussed on the existence of a humero-ulnar medial to lateral rotation. Using LED's mechanically connected to cadaver limbs, (Youm et al 1979) report photographic results of distal ulna translations during pronation and supination movements. Additionally, Amis states medio-lateral rotation at the humero-ulnar joint of the order of 10 degrees occurring during pronation and supination (Amis 1990). However, other researchers using radiographic techniques have detected no medio-lateral rotation at the humero-ulna joint (Chao and Morrey 1978)




| Width w (mm) |
|---|
| 58.23 |
| 58.23 |
| 58.17 |
| 58.21 |

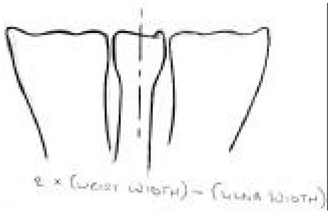
| Width u (mm) |
|---|
| 22.05 |
| 22.10 |
| 22.25 |
| 22.13 |

y = recorded values (mm)

| Y (mm) |
|---|
| 73.0 |
| 72.5 |
| 75.0 |
| 74.0 |
| 73.0 |
| 77.0 |
| 74.0 |

2

*x = 2*(wrist width)-(ulna width)*



| Expected value x=(2*w)-u (mm) |
|---|
| (2*58.21)-22.13) = 94.29 |

| Difference x-y (mm) |
|---|
| 94.3-74.0= 20.3 |

**Fig 5.4 Initial Pronation Supination Measurements**

Due to these uncertainties it was considered that measurements were needed to inform the design process. It was considered appropriate to a use a male with 50th percentile hand dimensions as the subject for these measurements. The same subject had been used in previous experiments which ensured continuity with the development of other analogous joints.

Initial measurements of wrist width, and ulna head were taken using digital vernier calipers. The wrist was palpated to find the styloid process of the radius (1), which was marked on the skin. This was chosen as due to minimal tissue coverage over this anatomical feature. The arm was then positioned on a sheet of paper with a line ruled on it. First the olercranon process (elbow bulge) was placed on this line, then the arm was positioned so that the third finger was aligned with the same line. With the arm in pronated position, using an engineers square, a mark was placed on the paper corresponding to medial position of the styloid process. This procedure was repeated with the arm in supinated position. The distance perpendicular to the scribed line on the paper between the marks was then recorded using a steel rule accurate to 0.5mm. The position of the hand in pronation and supination was approximately parallel to the plane of the paper in transverse section, Therefore it was reasoned for the ulna to remain stationary during this movement, a value of (2*(wrist width)-(ulna width)) would be expected to be the recorded distance on the paper (2).

During these initial experiments the wide error in the recorded results show that it was difficult to ensure humeral rotation was not influencing the results. However, a difference of approximately 1/3 of the width of the wrist between the expected result and the recorded result indicated that the mechanism of pronation-supination may be more complex than that of a single axis (figure 5.2 (1)). Consequently, more observational drawing from skeletal models was pursued to find indications of the mechanisms for more complex rotations.

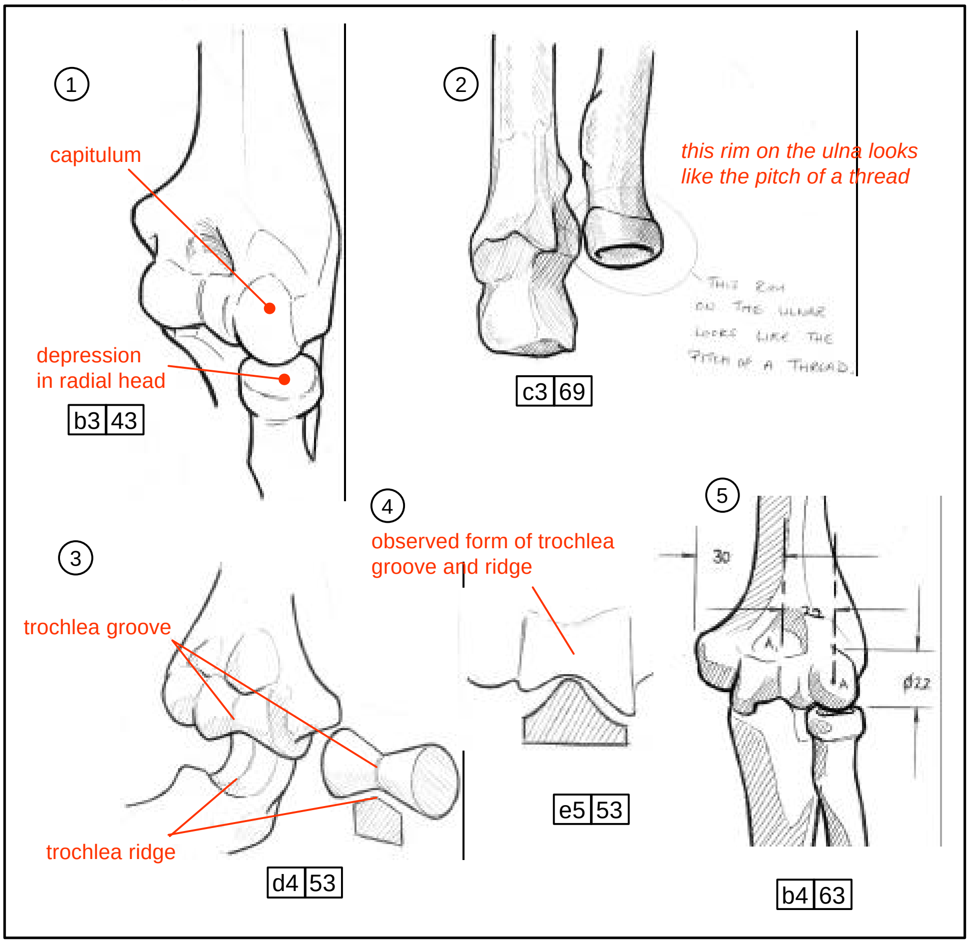
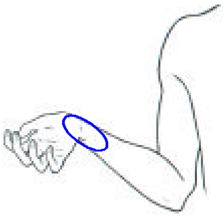



**Fig 5.5 Observational Drawing of the Forearm Joints at the Elbow**

Observational drawing studies from three-dimensional skeletal models indicated the capitulum to be approximately spherical, and the proximal head of the radius to possess a similar spherical concave depression. These observations were subsequently checked against the anatomical literature (Norkin and Levangie 1992) and was found to be correct. Initial literature review indicated that the humero-ulnar joint possesses a single degree of rotational freedom (Norkin and Levangie 1992). This possession of a single degree of freedom has been attributed to the highly contiguous fit of the trochlea ridge of the ulna within the trochlea groove (Kapandji 1982). However, the trochlea groove and trochlea ridge of the skeletal models was palpated and a large amount of freedom of movement was perceived. From observation of the form of the trochlea, it is evident that the groove is not sharp but akin to the depression around an hourglass (4). An observation confirmed in the literature (Norkin and Levangie 1992). The skeletal trochlea ridge of the ulna appears slightly sharper in its convexity than the trochlea groove is concave. This was initially attributed to the absence of cartilage in the skeletal joint. However, reference to photographic cross-sectional studies indicate the trochlea and trochlea notch not to be totally contiguous on the lateral border; possibly permitting a medio-lateral rotation (Guyot 1990). Due to the observed differences in the trochlea notch and groove it was reasoned that if a medio-lateral articulation exists it is likely to be close to the centre of the trochlea groove. Estimates of the distance between the centre of the spherical capitulum to the centre of the trochlea groove were made and marked on the observation drawings (5).





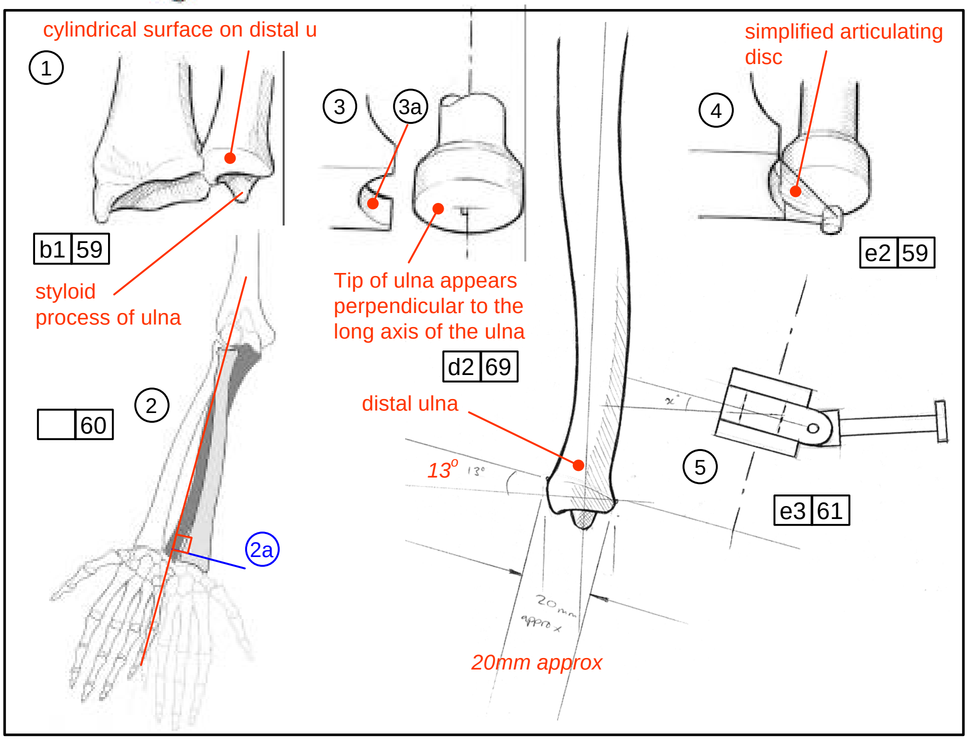



**Fig 5.6 Observational Drawings of the Distal Radio-Ulnar Joint**

The observational studies of the radius and ulna at the elbow were followed by studies of the distal radio-ulnar joint, as both these joints are stated as coupled during forearm rotation (Norkin and Levangie 1992). It was observed, and confirmed from the anatomical literature, that the distal radius possesses a concavity which articulates against a cylindrical surface on the distal ulna (1) (Kapandji 1982). From observational studies of this cylindrical surface, it did not appear to be orientated at an angle perpendicular to a line originating from the centre of the capitulum and extending to the centre of the head of the ulna (2a). Instead, the observed surface appeared angled either perpendicularly to the longitudinal axis of the ulna , or angled slightly proximally, medio-laterally. This apparent angle has been attributed to the truncation of the cylindical surface against the form of the distal ulna (Kapandji 1982). However, from observational drawing the whole cylindrical surface appears angled rather than truncated. Additionally, the distal tip of the ulna (3) was observed to be roughly perpendicular to the longitudinal axis of the ulna.

Further literature review indicated that the ligamentous structures between the radius and ulna are crucial in resisting translation of the radius relative to the ulna (Skahen et al 1997). Although these could not be observed on the skeletal models, it was reasoned that the role of the most distal radio-ulnar ligament, the articular disc (Norkin and Levangie 1992) might be deduced from observation of it's insertions and articulating surfaces. The articular disc inserts close to the ulnar styloid process (4) and onto the medial and frontal aspect of the of the radius (Kapandji 1982). It was reasoned that if this 'disc' is considered inextensible then the near perpendicular rim of the ulnar would guide the radius bone through a similar path, perpendicular to the long axis of the ulna (5).

It was noted that the concavity in the radius bone (3a) is larger in radius than that the radius of the ulna. Literature review indicated that radiographic research had found this in the intact distal radio-ulnar joint (Cone et al 1983).

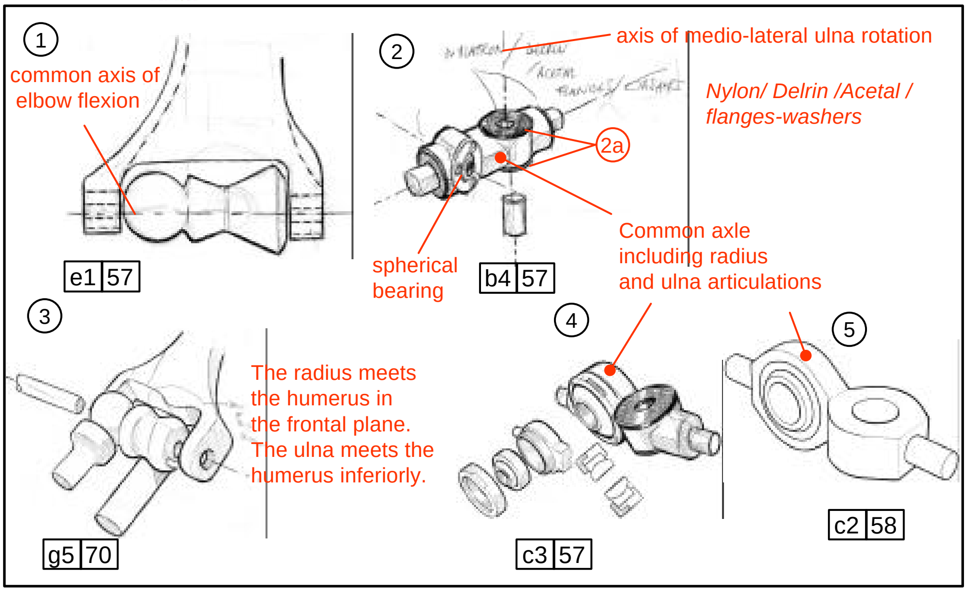
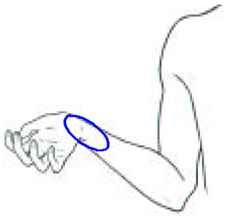



**Fig 5.7 Development of Proximal Radio-Ulnar Joint**

It was observed, and checked against the anatomical literature, that the elbow flexes on a common axis, that can be considered to run through the centre of the capitulum and the centre of the trochlea (Norkin and Levangie 1992). Therefore, an analogy was considered placing the spherical feature of the capitulum and grooved form of the trochlea onto a single axle (1) (see also chapter 6). Initially, the proximal capitulum to ulna joint was drawn as a ball and socket, however, this idea was superseded by ideas focussing on the use of a spherical bearing. The spherical bearing was chosen as it permits a mechanical connection between the two parts of the joint through the centre of the joint. Whereas, a ball and socket might require additional analogies of the radial collateral ligament and annular ligament that connect the radius to the humerus and ulna (Guyot 1990). Previous sketchbook idea development of the MCP joint had indicated that it might be difficult to realise a practical joint using an analogy of ligaments (concept development - chapter 4). It was reasoned that if the spherical bearing was connected to an axle common to the ulna, then it would only need to have a small range of rotation movement, permitting pronation and supination, as the major rotation of flexion and extension would be achieved by rotation of the whole axle (2) relative to the humeral fixture. It had previously been determined that the centre of the trochlea groove might be the site of medio-lateral humero-ulnar articulation. This articulation was proposed as a single axle (2). However, due to the size of the surfaces in contact, observed in the skeletal models, it was considered appropriate to provide two large thrust washers on both sides of the joint (2a) to limit further rotations. Observational drawing indicated the position the radius against the capitulum to be approximately perpendicular to that of the connection ulna to the trochlea (3). Therefore, sketch ideas for the axle proposed that the axle be machined to allow the spherical bearing to be fitted at 90 degrees to the axis of medio-lateral rotation of the ulna (2).

Several ideas to fix the spherical bearing within the axle were proposed. These included a using an internal circlip and a threaded cap (4). These ideas were discounted on the basis of adding complication to the design and compromising the strength of the axle. Existing mechanical fittings for hydraulic actuators show spherical bearings force fitted into their fixtures. This more simple approach has favoured and adopted for the final axle design(5).





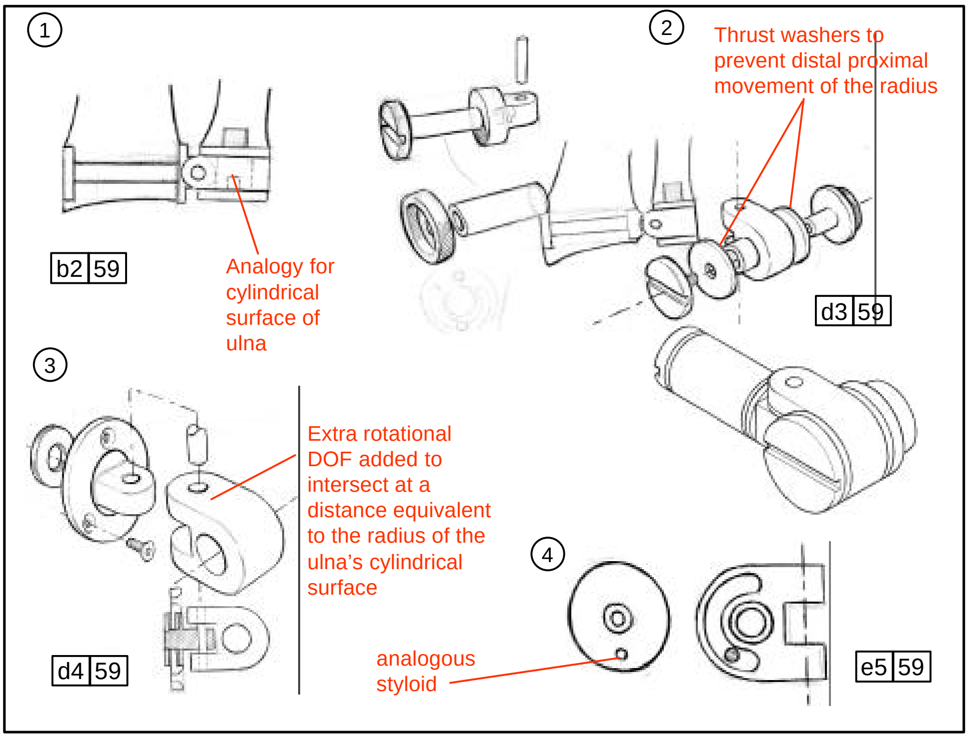
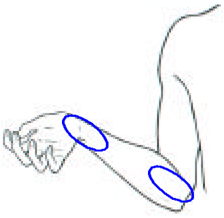



**Fig 5.8 Development of the Distal Radio-Ulnar Joint**

Observational drawing of the distal portion of the ulna indicated that movement of an articular disc against it this might act as a guide for the movement of the radius. As the distal surface of the ulna was observed to be perpendicular to the ulna's long axis, then this might guide the radius to rotate in a similar path. Sketchbook ideas were generated that would provide an analogy for the observed articulating cylindrical surface on the distal ulna (1). These ideas proposed the use of cylindrical bearings made from bearing plastic. A literature review indicated that 80 percent of the load on the hand is transmitted to the radius (Norkin and Levangie 1992). Consequently, plain thrust bearings were included into this joint design to design prevent uncontrolled distal or proximal movement of the radius relative to the ulna (2).

Observational drawing had highlighted the differences of curvature of the cylindrical surface of the distal ulna and the cylindrical segment from the distal radius. (Cone et al 1983) have reported relative movements between these surfaces during pronation and supination. It was reasoned that if relative angular movement must occurred, it would be at the interface of the two articulating surfaces; i.e.at a point on the radius of the curvature of the ulna head. Therefore, sketchbook ideas proposed adding additional orthogonal axes of movement to the distal radius, intersecting at a point equivalent to the radius of curvature of the distal ulna (3). Anatomical texts indicate that the range of movement of pronation and supination is effected both by the musculature of the arm but also by ligaments such as the quadrate, and anterior-posterior radio-ulnar ligaments becoming taut ( Norkin and Levangie 1992). The form of the radius and area around the ulna styloid is also factor in limiting pronation and supination movement (Kapandji 1982). An analogy of the ulna styloid was proposed as means of limiting the angular movement of the model joint. This was proposed by to be a semicircular track in the rotating U component in which the analogous styloid would run (5).



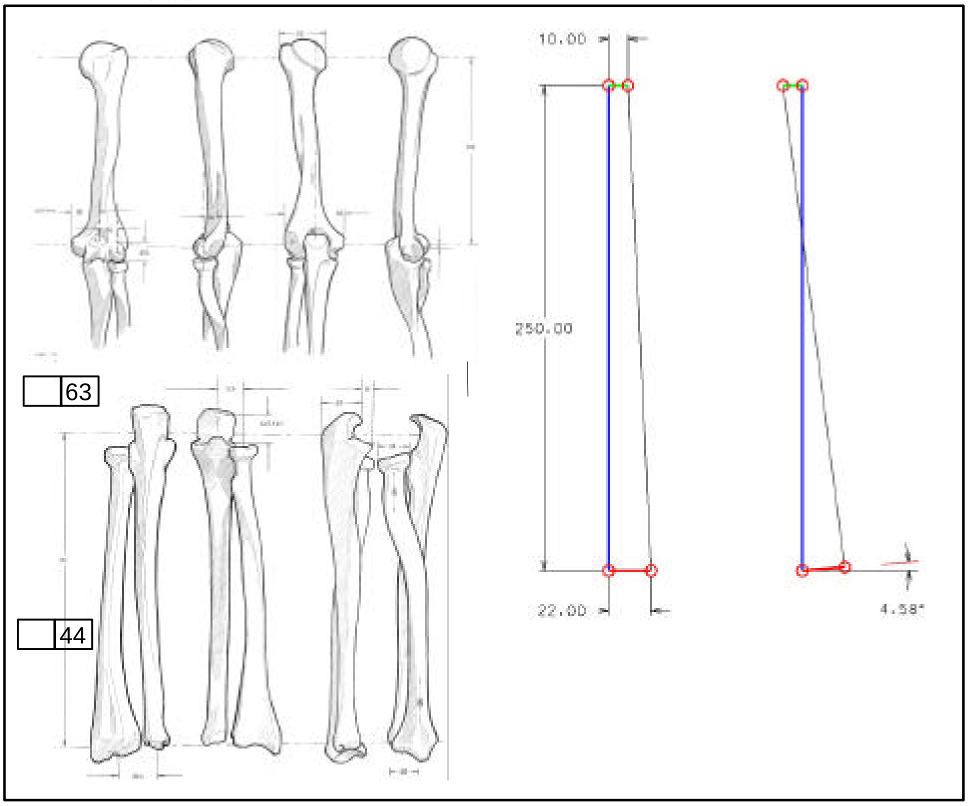
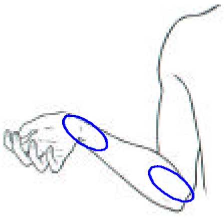



**Fig 5.9 Observational Drawing**

The observational drawing previously undertaken was used a basis for two dimensional trigonometric analysis to understand how the proposed joints would function when coupled together. During the observational drawing studies approximate measurements of anatomical features were recorded using a steel rule accurate to 0.5mm and annotated on these drawings. The distance from the centre of the trochlea notch to the distal centre of the ulna head (blue) was recorded as 250mm; the distance between the centre of the capitulum and the trochlea groove (red) estimated at 22mm, and the radius of the cylindrical surface on the distal ulna (green) estimated at 10mm. Two views of this set of links were draw, one in relating to the supinated position where the green link is to the right of the blue link, and a pronated view in which the green link has been rotated 180 degrees perpendicularly to the blue link to be to its left. As the bones of the forearm are not understood to deform under normal pronation-supination movements the links joining the articulations were considered of the same length in both cases. For ease of calculation the blue link was considered stationary to the remaining links rotating relative to that. Using simple trigonometry it was calculated that the red link would move through an angle of 4.6 degrees (counter clockwise) on full pronation. The red link represents the centre line on which ulna and radius rotations take place, however, these centres are colinear with the main axis of elbow flex in the model. In the initial measurements it was this axis that had been chosen as the datum from which parallel translations of the distal ulna had been measured. Therefore, considering the red link stationary a *clockwise* rotation of the ulna of 4.6 degrees represents a translation of Sin (4.58)*250mm = 20mm parallel to the red link. This was identical to the values recorded from the intact limb, and so the joins designs were detailed for prototype production.





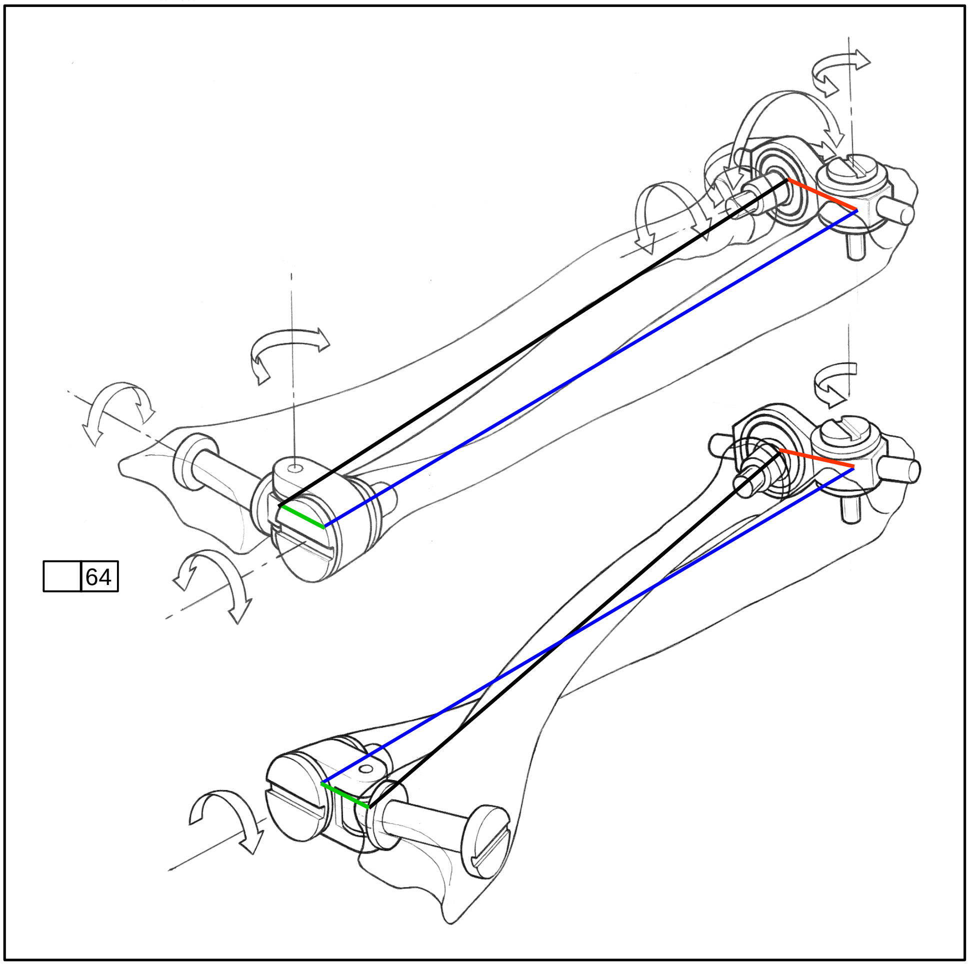



**Fig. 5.10 Radius and Ulna Complete With Calculation Links**

This figure shows how the intersection of the axes of rotation of the joint form the intersection of the links for the simple mathematical model used in the development of the joints.

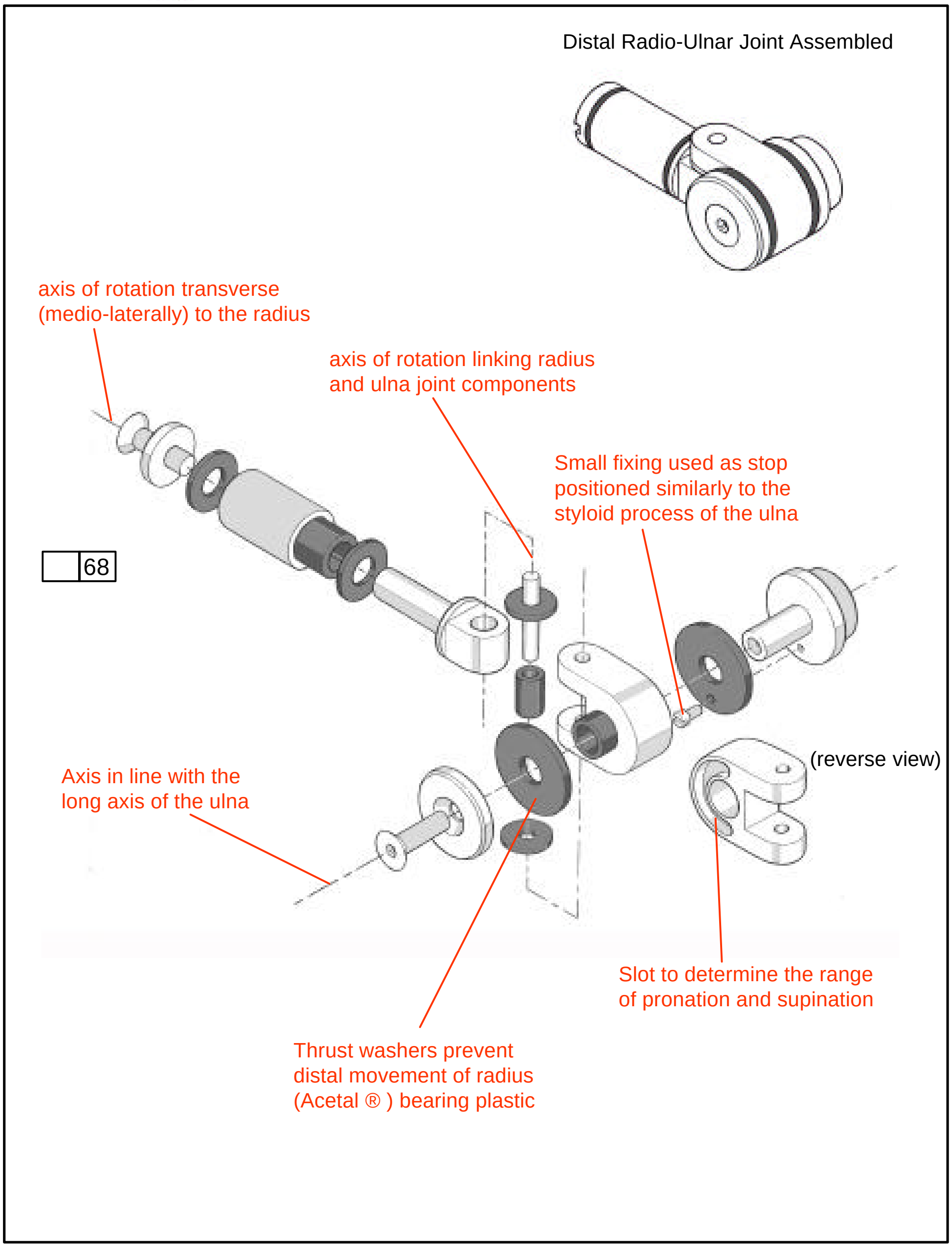
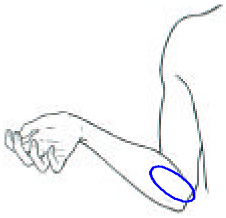



**Fig. 5.11 Exploded View of the Distal Radio-Ulnar Joint**

This figure shows the components of the model distal radio-ulnar joint, along with indications to the design principles embodied within the design.





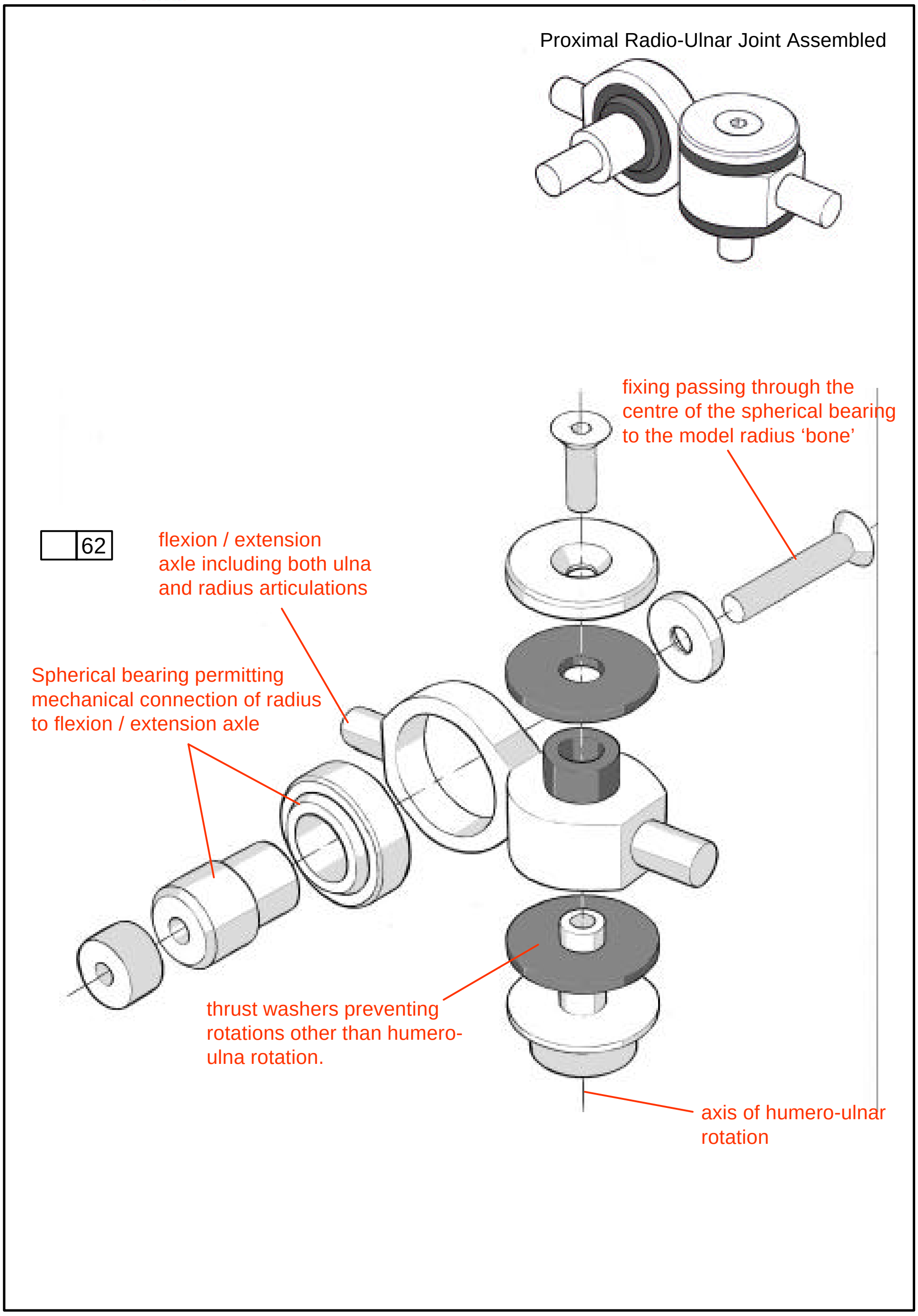
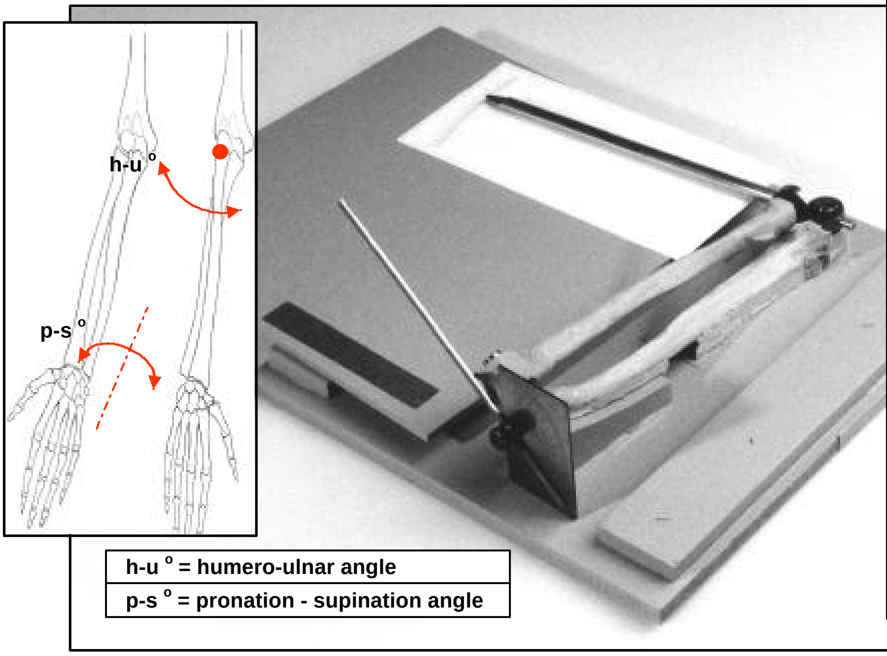



**Fig 5.12 Exploded View of the Proximal Radio-Ulnar Joint**

Similarly to the previous page this figure shows the model proximal radio-ulnar joint and along with indications of the functions of some of its components.



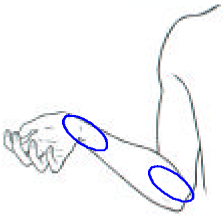

| h-u ° | p-s ° |
|---|---|
| 0.00 | 0 |
| 0.50 | 10 |
| 1.00 | 20 |
| 1.45 | 30 |
| 2.00 | 40 |
| 2.75 | 50 |
| 3.22 | 60 |
| 3.75 | 70 |
| 4.22 | 80 |
| 4.33 | 90 |
| 4.58 | 100 |
| 4.97 | 110 |
| 5.22 | 120 |
| 5.23 | 130 |
| 5.30 | 140 |
| 5.33 | 150 |
| 5.17 | 160 |
| 4.83 | 170 |
| 4.53 | 180 |

**Fig 5.13 Joints Measured within Resin Casts of Human Radius and Ulna**

The proposed articulations of the model joints, although requiring close tolerances, were all simple geometrical forms. Therefore, it was considered that conventional machine tool processes would be appropriate for prototyping. The structure of the joints was specified to be a 'freecutting' mild steel, whilst an Acetal ® copolymer was chosen as a suitable bearing plastic. As with the development of the wrist and finger joints many ancillary holding 'jigs' were required.

Once the joints were made, the skeletal model which had served as the subject of observational drawing, measurement and calculation, was used to make high definition silicone rubber moulds of the radius, ulna and humerus bones. Once these moulds were complete a low contracting rigid polyurethane casting resin was poured into the mould cavities. An MDF mounting board was made with a line scribed parallel to one of its edges.

The resin bones were then taken from the moulds and arranged in a posture with the ulna and radius flexed at approximately 90 degrees to the humerus, with the long axis of the ulna parallel to the scribed line on the mounting board. The radius and ulna were positioned in supinated posture, whilst a two part polyester resin of a contrasting colour was applied between them. Once this had cured the humerus was removed and the mounting board taken to a vertical milling machine. The scribed line on the board was aligned with one of the axes of the milling machine. The centre of the trochlea notch was approximated on the resin cast, and this was taken as a datum. Using this datum 'pockets' were machined into the casts to insert the joints at positions corresponding to the calculated link lengths. The joints were secured to the bones with more polyurethane resin. Subsequently, resin binding the bones together was removed and the model was pronated and supinated. A mark was placed on the styloid process of the model radius and a lightweight extension arm fixed to the flexion-extension axis proximal radio-ulnar joint. The model ulna remained firmly fixed to the mounting board with polyester resin. Measurements were then taken of the angular position of the proximal flexion extension axle with respect to changes in angle of pronation and supination.





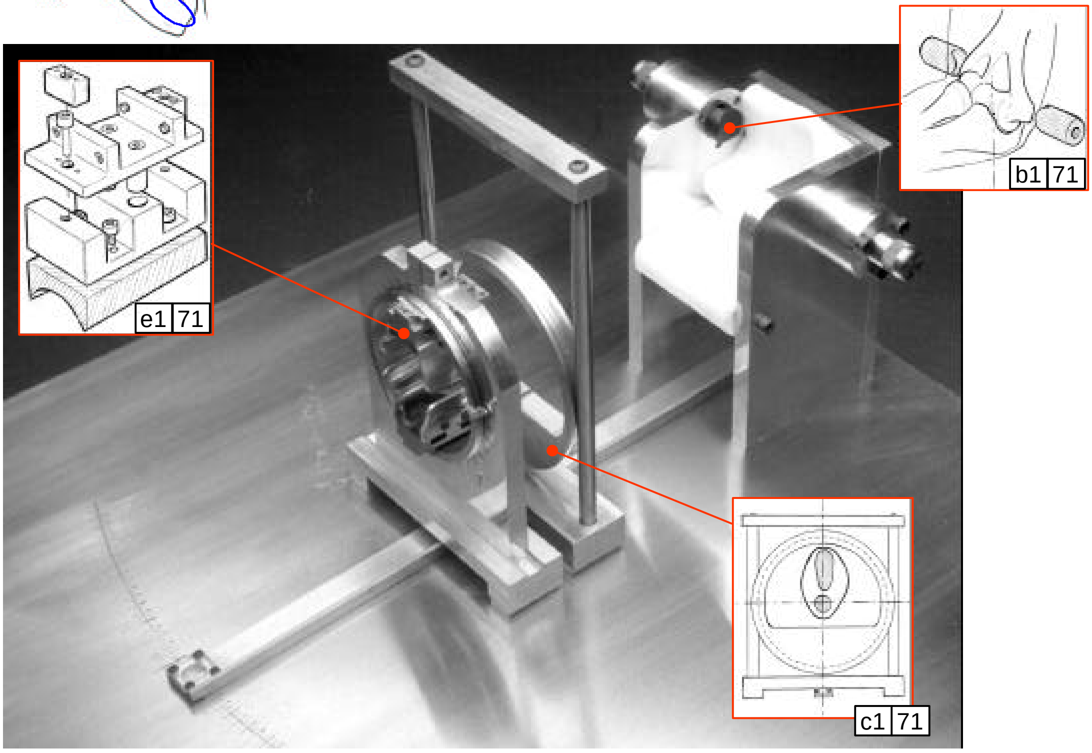



**Fig 5.14 Pronation-Supination Splint**

Previous studies on the pronation-supination movement of the human arm have been performed on cadaverous arms (Youm et al 1979). Principally this has been done so that rigid markers can be a fixed to the skeleton. Rigid mechanical connection is considered necessary as the majority of the radius and ulna lie deep within soft tissue (Kapit and Elson 1993). More recent studies (Nakamura et al 1994) have been performed using Magnetic Resonance Imaging. However, with these experiments it is unclear how the splints required to fix the arm within the imaging device constrain the movements of the arm. Conflicting results have been reported using radiographic methods: the research findings of (Cone et al 1983) report no evidence for a medio-lateral articulation at the humero-ulna joint whilst (Amis 1990) reports radio graphic evidence supporting a medio-lateral articulation up to 10 degrees.

To ascertain how closely the prototype joints were reproducing the movement of the ulna during forearm rotation it appeared appropriate to take measurements from an intact limb, where all the constraints of a mechanical splint were know. A male of normal build was chosen as the subject for these measurements. A close fitting splint was tailor made for the subject. A large plain annulus bearing (a) was manufactured with adjustable close fitting adjustable wrist clamps (b). This was housed in a fixture with increments of 10 degrees marked upon it. The wrist clamp for the ulna was mechanically connected to a grooved hollow disc (c) . Using an accurate vernier height gauge the disc was positioned so that the centre of the ulna was coincident with that of the disc. The grooved disc rotated between two parallel ground bars connected to a stand with a ‘peg’ projecting from its centre to line with one of the centre lines of the grooved disc. The Proximal part of the forearm was secured in a elbow fixture with two pegs securing the humeral medial and lateral epicondyles (d).

1

| p-s ° | h-u ° |
|---|---|
| 0 | 0.00 |
| 10 | 0.00 |
| 20 | 0.10 |
| 30 | 0.25 |
| 40 | 0.58 |
| 50 | 1.08 |
| 60 | 1.58 |
| 70 | 2.08 |
| 80 | 2.34 |
| 90 | 2.83 |
| 100 | 3.67 |
| 110 | 3.92 |
| 120 | 4.34 |
| 130 | 4.67 |
| 140 | 5.00 |
| 150 | 5.50 |
| 160 | 6.17 |

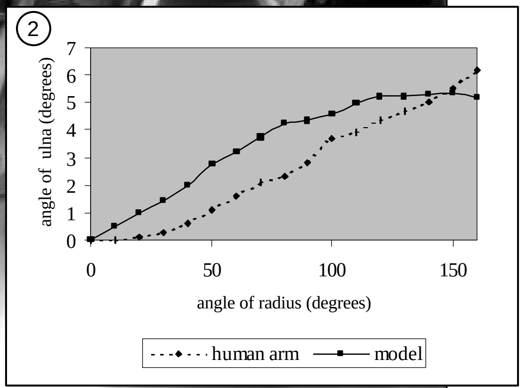
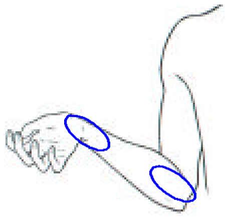



**Fig 5.15 Pronation-Supination Splint**

Vertically beneath the elbow fixture aligned with the approximate centre of the olercranon was a peg onto which indicating bar (a) rotated. The peg aligned with the grooved disc was also connected to rotate with a slot within the indicating bar. Both the fixture for the wrist and grooved disc were manufactured with to slide on PTFE (polytetrafloroethylene) blocks. The mounting board was made from polished aluminium sheet, onto which additional low surface tension lubricant was sprayed to further reduce friction between the mounting board and the distal clamping fixtures.
The subject was firmly secured in the jig and the forearm rotated in 10 degree increments, whilst the angular position of the ulna was recorded from the indicator bar. The experiment was repeated three times, the mean values being recorded on table (1).

The graph (2) shows the difference between the movement of the model ulna and that of a human ulna during pronation-supination movements. It evident that rotation of the bones was occurring before being indicated by the scale on the annulus bearing, due to relative movement of soft tissue within the wrist clamps, thus supporting the need for direct connection to the skeleton (Youm et al 1979) . This was estimated by twisting the clamp wrist retaining the wrist in full supination. Although the clamps were tight around the wrist it was found that this movement accounted for an intial estimated error of 10-20 degrees due to the skin becomming taut before movement was recorded. All measurements were taken using 0 degrees (full supination) as the start position. Therefore, although currently there is a wide discrepancy between the angular positions in the mid range, this can slightly offset by soft tissue errors, if the maximum estimated error of 20 is used this bringing the maximum discrepancy down to less than 1 degree, or less than 4mm of ulna translation.





## Discussion

The process of creative reasoning has been used again in the development of the linked forearm joints. Using observational drawing from three dimensional anatomical models it was found that details of the anatomy could be elucidated that proved important in the design of the analogous joints.

In the development of the forearm joints it has been found necessary to supplement the creative reasoning process with a stage of mathematical analysis. As it was found that exploring the effects of the linked the distal and proximal joints was too complex using purely sketch book idea development.

Conventional machining techniques were considered appropriate for the prototyping of these joints. Unlike the finger joints these joints have individual forms requiring machining from many directions. Additionally, some of the joint components have relatively simple forms, again suiting conventional machining techniques.

It was considered appropriate to use resin casts of the human radius and ulna bones to connect the joints to initially test the movement of the joints. However, this may suggest possible ‘strut’ forms suitable for an eventual prosthesis using the appropriate choice of material.

Specially designed splints were constructed to compare the movements permitted by the joint designs against those of the human forearm. This was done as from the literature it was evident that there were uncertainties about the nature of forearm pronation / supination movements in the intact arm. However, using the splint method significant error was found due to the effects of soft tissue.

It was considered that for a meaningful qualitative evaluation of the movement permitted by the forearm joints it was necessary to first develop an elbow fixture. The development of the elbow is detailed in the following chapter.